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Secondary electron emission of tin and tin-lithium under low energy helium plasma exposure

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ABSTRACT

Secondary electron emission (SEE) yields of tin (Sn) and tin-lithium (SnLi) eutectic (20 at.% Li) samples were measured in He-plasma at a mean incoming electron energy up to 120 eV. SnLi shows a maximum yield of about 1.45 at 110 eV electron energy while the yield of the Sn surface was measured to be maximally 1.05 at 120 eV. X-ray photoelectron spectroscopy (XPS) analysis demonstrated the segregation effect of Li to the surface of the eutectic, both after melting in the argon atmosphere and in molten state with simultaneous He-plasma exposure. At least the top 10 nm of the SnLi samples were heavily enriched with Li, and Sn/Li ratios varied in the range 0.8–5% depending on eutectic treatment conditions. After the plasma exposure Sn3d is detected predominantly in the oxidized state while after extended atmospheric oxidation there was still a significant amount of Sn3d detected in the metallic state. The liquid surface of SnLi indicated a possible decrease of SEE yield. All measurements gave values of SEE yield close to or above unity. Such values can lead to significant plasma sheath disturbances and subsequent additional heat flux from electrons on such a plasma-facing material, thus, should be accounted for in designing fusion reactors using these components.

1. Introduction

Over the last two decades the concept of a liquid metal divertor for a post-ITER nuclear fusion reactor i.e. DEMO has attracted increasing attention [1–3]. Studies suggest liquid metals have favorable properties in terms of power exhaust and self-healing [4–6]. Lithium and tin are considered as two of the most promising candidates due to their physical and chemical properties. For lithium (Li) these include: low-Z value, hence a higher level of impurities can be tolerated before fusion power is significantly degraded; a low melting point; and improved discharge stability in tokamaks [7–9]. As for tin (Sn), it has a wide operational window due to its low melting and high boiling point in combination with a relatively low evaporation rate and could potentially exhaust power densities up to 20–25 MW/m^2 [5,10]. The idea to use the advantages of both metals in the eutectic of SnLi has been proposed in several papers such as [11–13], but the properties of such the eutectic when exposed to a plasma are not well studied. Thus, the characterization of the eutectic in comparison to its constituent elements is still necessary.

An important property of a plasma facing material (PFM) is the rate of emission of secondary electrons relative to the incoming particle fluxes. The secondary electron emission (SEE) yield represents the outgoing amount of electrons per each incident electron as a function of the energy of the incoming particle. Generally, at energies below several hundred eV only the emission stimulated by electrons is important [15] and therefore we restrict our discussion and study here to the electron stimulated emission. SEE can lead to a modification of the sheath which consequently will increase the floating potential and provide an additional heat from increased electron flux [14,15]. The magnitude of the extra heat arriving at the surface originating from high SEE can be several times larger than the heat flux on a material with no or marginal SEE yield (Y_{see}) [14]. Therefore, the power exhaust capability of a metal surface can be limited by this process.

The influence of SEE on plasma sheath and the corresponding rise of the heat flux was estimated in several works such as [14–17]. The classical sheath model can still describe marginal SEE [15,18,19], but even in this case when Y_{see} approaches unity the SEE impact on the sheath layer is significant, as can be seen through Eqs. 1 and 2 which represent the floating potential (V_f) and the electron heat flux ($q_{e,\ surf}$) to the surface respectively [15]:

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$$V_f = -\frac{kT_e}{2e} ln\left[\frac{\frac{2\pi m_e}{m_i}\left(1+\frac{T_i}{T_e}\right)}{(1-Y_{see})^2}\right] \quad (1)$$

$$q_{e,\ surf} = \frac{2kT_e j^-}{(1-Y_{see})e} \quad (2)$$

where k is the Boltzman constant, m_e, m_i are respectively the masses of electrons and ions, T_e, and T_i are respectively the electron and ion temperatures, Y_{see} is the secondary electron yield and j^- is the electron current density striking the surface.

As can be seen both equations approach infinity as Y_{see} approaches unity and the sheath model is therefore insufficient. A modified sheath to account for this can be described with a space-charge-limited (SCL) model, where a virtual cathode appears in the sheath, limiting the electron losses from the surface [20–23]. Furthermore, when the yield is even larger some models predict a reverse sheath (RS) [24–27]. The SCL model suggests an increased heat flux and a corrected floating potential, but the RS model implies that the sheath can be reversed or even disappear [26]. This will lead to extremely high heat load because electrons will not be decelerated at all in the sheath (as considered in the classical model) and thus an increased flux of power and electrons will be deposited on the PFM. This can therefore substantially limit the power exhaust capability of such a material.

In this paper we measure the Y_{see} of Sn and SnLi under low energy He-plasma exposure, as they are considered to be prospective candidates for a liquid divertor concept. In particular, the Y_{see} of SnLi has not previously been measured, while this represents the first time this measurement methodology is used for the Y_{see} of Sn. The segregation of Li to the surface of the eutectic mixture is also studied before and after exposure using X-ray Photoelectron Spectroscopy (XPS).

The experimental apparatus and arrangements are described in Section 2.1. The sample design and the preparation process is given in Section 2.2, while Section 2.3 outlines the experimental procedure and results. Finally, the discussion of the obtained measurements and conclusions are given in Sections 3 and 4, respectively.

2. Experimental apparatus and procedures

2.1. Setup

A detailed description of the experimental setup is given in [28,29]. In this section we briefly outline the main elements and specify the important modifications that were made. The vacuum chamber consists of an anode; a port for a sample holder with a built-in heater and a thermocouple; and another port for a disk probe with a grid [30] (figure 1). A glow discharge is created in a helium gas between the walls, which are grounded and act as the cathode, and the anode. Each sample was exposed to glow discharges at a variety of gas pressures. This variation was used to make a valid determination of the electron energy distribution and accurately determine error bars. The following discharge parameters were varied depending on the experimental series, with higher voltages and currents used at higher gas pressures: the discharge voltage (220 − 400 V), the current (275 − 525 mA) and the gas pressure (1.6×10^{-3} to 8×10^{-3} mbar). In this range of parameters, we previously measured electron densities of 4×10^{14} $m^{-3} - 1.03 \times 10^{15}$ m^{-3} and electron temperatures of 6.5 − 10.4 eV [29]. The background pressure was 2×10^{-6} mbar and the heater temperature was varied in the range 295 − 623 K dependent on the choice of the solid or the liquid surface to be measured.

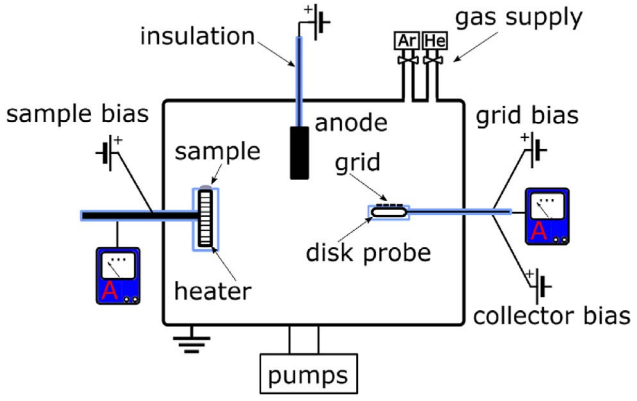

Fig. 1. Experimental setup. A vacuum chamber has several inlet ports for a sample holder with a built-in heater and a thermocouple on one side and for a disk probe on the other side.

2.2. Sample preparation and characterization

Samples were made of tin or tin − lithium eutectic (nominally lithium 20 at. %, Princeton Scientific Corp.). Round stainless steel (SS304) disks of 20 mm were used as a substrate. The substrate surface was mechanically polished to ~100 μm roughness and chemically treated with concentrated hydrochloric acid (37%) to provide a good adhesion of the molten metal to the substrate (Fig. 2). The Sn and SnLi were melted in a separate vacuum chamber with a residual gas pressure of about 6×10^{-7} mbar. The substrate surfaces were then coated with the molten metal and subsequently cooled to the room temperature in vacuum prior the transfer to the exposure chamber. The coating thickness was measured to be 5 mm.

It was previously observed that the SnLi composition evolves under melting, leading to the enrichment of the surface with Li relative to the stoichiometric ratio [12]. To attempt to understand the actual surface which produces the SEE, SnLi samples were analyzed using X-Ray Photoelectron Spectroscopy (XPS) to investigate the heating and melting influence on such a SnLi surface. Two SnLi (20 at.% Li) eutectics were analyzed: one produced using a similar procedure as [13] (type 1) and another using supplied by Princeton Scientific Corp. (type 2). These eutectics were used to study three different states of a sample.

The first state was as received from the manufacturer and analyzed with XPS (made from type 1, notation “as received” in Fig. 3). This sample had predominantly been stored in a sealed air-tight container prior to measurement.

The second state was after melting in an argon atmosphere, subsequent solidifying, but no plasma exposure (made from type 1, notation “Ar melt” in Fig. 3). Its only atmospheric exposure was during transfer to the XPS machine. The purpose of melting in argon (inert

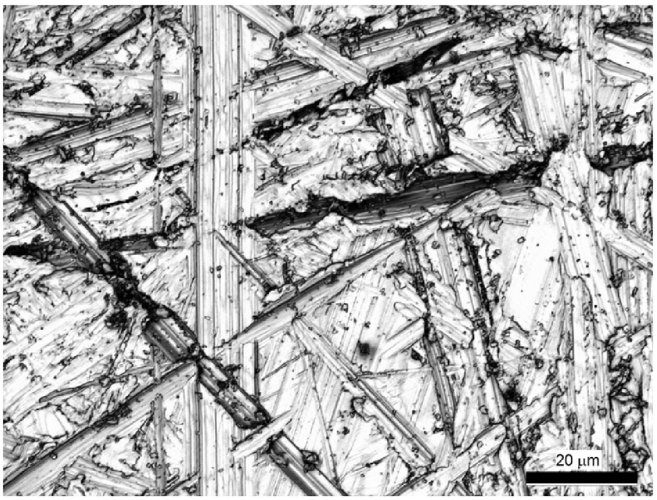

Fig. 2. A microscope picture of a substrate surface after the mechanical polishing and the etching in the concentrated hydrochloric acid.